Chapter 1
Industrial Ecology's First Decade

T.E. Graedel and R.J. Lifset

Abstract Industrial ecology can be said to have begun with a 1989 seminal publication entitled "Strategies for Manufacturing." During the next decade, the field was initially defined and developed by researchers in industry and elsewhere who saw the opportunity for improving corporate and governmental performance related to the environment and sustainability. They introduced design for environment, industrial symbiosis, and resource use and loss assessments at national and global levels and enhanced the embryonic specialty of life-cycle assessment. In the same decade, industrial ecology became widely recognized as a scholarly specialty, with its own journals and conferences. This chapter reviews industrial ecology's emergence and evolution, largely from a North American perspective, with emphasis on the field's lesser-known first decade.

Keywords Emerging discipline • Evolution of industrial ecology • History of industrial ecology • International society for industrial ecology • Journal of industrial ecology

1 Origins of Industrial Ecology

The 1972 United Nations Conference on the Human Environment in Stockholm is often seen as milestone in the emergence of a global environmental movement. The declaration arising from that conference included twenty-six principles, including several that resonate with what we now know as industrial ecology:

Principle 2: The natural resources of Earth… must be safeguarded for the benefit of present and future generations.
Principle 5: The nonrenewable resources of Earth must be employed in such a way as to guard against the danger of their future exhaustion.

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Principle 6: The discharge of toxic substances… in such quantities or concentrations as to exceed the capacity of the environment to render them harmless must be halted.

Slightly preceding the Stockholm conference, however, was the establishment of the US Environmental Protection Agency (EPA) in 1970. Over the next several decades, the EPA developed air and water pollution control activities seeking to achieve the sorts of goals articulated in Stockholm's Principle 6, creating regulatory oversight of emissions and the implications of those emissions on human health. The preservation of resources entered the picture with the widely read book *Limits to Growth* (Meadows et al. 1972), but this issue, with the exception of oil, received only passing attention in the 1970s, both by governments and corporations.

Erkman (1997) has demonstrated that several intellectual threads that eventually became part of industrial ecology were under development in the 1970s and 1980s: the concept of industry as an ecosystem, the quantification of material and energy flows, and the relationships of technology to the general economy. Japan, in particular, moved during this time toward using advanced technology to limit its demands for materials and energy (e.g., Watanabe 1972; MITI 1988). This approach embedded industrial ecology thinking in industry to a greater degree than existed elsewhere at that time, a distinction that to some degree remains true today.

Almost 30 years after the 1972 Stockholm conference, Robert Frosch and Nicholas Gallopoulos of the General Motors Research Laboratory published a paper with the modest title "Strategies for Manufacturing." In this paper, Frosch and Gallopoulos (1989) discussed the environmental impacts of manufacturing, speculated that resource depletion and waste accumulation would be challenges in the coming years, and provided an innovative approach to address these issues:

> The traditional model of industrial activity … should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized, and the effluents of one process … serve as the raw material for another.

With these words, Frosch and Gallopoulos inaugurated the field of industrial ecology.

2 Constructing the Field of Industrial Ecology

Frosch and Gallopoulos were employees of General Motors, rather than university researchers, and were advocating an environmental ethic that went beyond complying with existing regulations. Their call to action was soon recognized as acknowledging what some corporations were already doing, or upon which they were soon to embark. Frosch and Gallopoulos were not the only ones thinking along these lines but were among the first to put a public face on these efforts. An admittedly incomplete list of some of the most active corporations during the seminal period 1988–1996 includes Volvo (1991; Horkeby 1997), 3M (Holusha 1991), BMW (Holusha

1991), Xerox (Murray 1993; Azar et al. 1995), Procter & Gamble (Pittinger et al. 1993), Pitney Bowes (Ryberg 1993), AT&T (Allenby 1994), Motorola (Hoffman 1995, 1997), IBM (Bendz 1993; Kirby and Pitts 1994), Hewlett-Packard (Bast 1994), Philips (Boks et al. 1996; Stevels 2001, 2009), and Bosch (Klausner et al. 1998). The mantle was also taken up by industrial associations, particularly the electronics industry (Microelectronics and Computer Technology Corporation 1994; Sony (Scheidt and Stadlbauer 1996); and NEC (Suga et al. 1996)).

It is fair to say that while some corporate initiatives were inspired by altruism to a significant degree, those who were involved had other motives as well: simplification of assembly and disassembly of products (Lundgren et al. 1994), reuse of material resources (Porada 1994), and recovery and recycling of components (Azar et al. 1995; Nagel 1997), among others. One of the most dramatic corporate initiatives in the early years of industrial ecology was that of Volvo, which worked with Swedish academic and governmental organizations to produce one of the first workable versions of life-cycle impact assessment (Steen and Ryding 1992) and then used the results to influence the design of Volvo products (Horkeby 1997).

Most of the early corporate and governmental initiatives related to industrial ecology were uncoordinated and ad hoc. This situation began to change with a conference held in 1991 at the US National Academy of Sciences (Patel 1992). Attendees at that meeting began the process of identifying what topics should be included in an industrial ecology framework (material cycles, energy efficiency, input–output analysis, etc.). A 1992 conference in Colorado (Socolow et al. 1994) expanded that framework to incorporate human impacts on natural cycles, IE in manufacturing, and IE in policy-making. In subsequent years, the field has proceeded in fairly straightforward fashion from those foundations. That conference also provided the name for the field. As Socolow (1994) describes in the introduction to the book that came from the conference (Socolow et al. 1994), the choice was between "industrial ecology" and "industrial metabolism" (Ayres 1989). As conference chair, Socolow chose the former as being the more encompassing of the two options and one that brought such ecological topics as food chains and resource reuse into the discussion. Perhaps largely because conference attendees included a number of those who went on to research and write about this area of study, Socolow's choice stuck. Nonetheless, metabolism has remained an important concept and analogy in the field (e.g., Octave and Thomas 2009; Gierlinger and Krausmann 2011), providing a rich and growing framework for much of the material flow analysis that is central to industrial ecology.

Governments joined the industrial ecology effort soon after its identification by corporations (e.g., MITI 1988; Office of Technology Assessment 1992; U.S. Environmental Protection Agency 1995). Nonetheless, it is noteworthy that, unlike many other fields of study, the origins of much of industrial ecology lay not in academia but in industry. IE is today regarded as an academic specialty, but it continues to rest on the foundation developed and practiced by industry and, to some extent, by governments.

Industrial ecology was thus becoming a recognized field in the mid-1990s, but what exactly *was* industrial ecology? An early definition by the president of the US

National Academy of Engineering attempted to encapsulate what the concept was all about:

> Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of those flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. (White 1994)

This definition remains, 20 years later, as a reasonably good synopsis of the field. However, an alternative and more expansive definition was provided a year later:

> Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital. (Graedel and Allenby 1995: 9)

This second definition extends the field outward from a solely industrial focus to a more societal one and introduces the issue of sustainability. In the twenty-first century, this enhanced concept has strongly influenced the way industrial ecology is practiced. In fact, a recent "sound bite" definition of industrial ecology, "Industrial ecology is the science behind sustainability," (Makov 2014) almost bypasses the industrial focus in the interest of a planetary focus.

Regardless of which definition a particular individual may prefer, a few key words appear to indicate the scope and focus of the field: industry, environment, resources, life cycle, loop closing, metabolism, systems, and sustainability.

3 Building the Tools of the Trade, 1990–2000

3.1 Life-Cycle Assessment

Life-cycle assessment (LCA) is the methodology that seeks to identify the environmental impacts of a product or process at each stage of its life cycle. Analytical efforts to quantify emissions and resource loss on a life-cycle basis date from the 1970s (e.g., Bousted 1972; Hunt and Welch 1972), but LCA's rapid growth and its close relationship with industrial ecology began about 1990, especially in Sweden (Steen and Ryding, 1992), and it first became codified in a 1993 handbook (Heijungs et al. 1992). Klöpffer (2006) has reviewed the key role of the Society for Environmental Toxicology and Chemistry (SETAC) in the early development of LCA. In Europe, a spur for the development of a standard methodology came from the adoption of LCA as the basis for product labeling (Clift et al. 1994). While the need for further development of the methodology was widely recognized (e.g., Field et al. 1993), adoption of LCA as an industrial ecology tool became increasingly widespread, both in industry and government (Harsch et al. 1996; Matsuno et al. 1998; Itsubo et al. 2000).

A lively community of methodology developers and practitioners emerged, and LCA benefited from database development, standards setting, and creation of software. However, some potential users (especially in industry) found the methodology too complex and contested to be workable on a routine basis. This led many to work with the LCA consulting industry that sprang up to respond to a demonstrated need and the increasing availability of LCA software. An alternative approach was to "streamline" LCA (e.g., Graedel et al. 1995; Weitz et al. 1995; Hoffman 1997; Christiansen 1997), and streamlined LCA (SLCA) has since been used in various forms throughout industry. As a consequence of these initiatives, LCA and SLCA activities in industry are much more significant than might be inferred by an outside observer.

In 2002, a new LCA guide addressed in detail many of the issues that had caused concern in the past (Guinée 2002). However, unresolved problems remained, as pointed out by Reap et al. (2008a, b). LCA remains today in the interesting position of being viewed as still in development as an academic tool but widely employed in industry. It will doubtlessly continue to undergo further development, as it continues to provide important perspectives on industrial product and process design activities.

3.2 Design for Environment

The recovery and reuse of a variety of "industrial resources" was rather common early in the twentieth century (Desrochers 2000) but became more challenging as materials, components, and products became increasingly complex and as resources appeared abundant. However, in the late 1980s, a number of corporations began to rethink their product design processes, especially as those processes related to recycling or resource loss (Henstock 1988). The result was methods that looked beyond product performance, appearance, and price to attributes such as efficient manufacturing, fewer parts suppliers, and less inventory (Watson et al. 1990). From that perspective, it was an easy step to consider environmental factors such as minimizing energy requirements, decreasing discards from manufacturing, choosing more sustainable materials, and the like (e.g., Hamilton and Michael 1992; Kirby and Pitts 1994; Azar et al. 1995; Sheng et al. 1995). Among several related books, the 1996 volume *Design for Environment* (Graedel and Allenby 1996) stimulated interest among industrial design groups throughout the world (e.g., Klausner et al. 1998; Stevels 2001). Aspects of disassembly, remanufacture, and recycling, widely discussed in the 1990s, have continued to be emphasized (Cândido et al. 2011; Go et al. 2011; Hatcher et al. 2011; Ryan 2014).

Design for environment is becoming increasingly embedded in both the educational and industrial aspects of product design. Perhaps the best evidence for this is the broad acceptance of the 2009 book *Materials and the Environment: Eco-Informed Materials Choice*, by Cambridge University engineering professor Michael Ashby (Ashby 2009). This volume is widely used in undergraduate education and in the industrial design sector, an achievement that is perhaps one of the more significant (if not the most visible) contributions of the industrial ecology field thus far.

3.3 Material Flow Analysis

Material flow analysis (MFA) is the methodology for quantifying the stocks, flows, inputs, and losses of a resource. It is sometimes used for mixed materials (e.g., construction minerals) but more commonly is directed to a specific resource such as a particular metal or plastic. For specific resource applications, the methodology is sometimes termed substance flow analysis (SFA). Early MFA research was conducted by Robert Ayres when he was at Carnegie Mellon University in Pittsburgh, PA. In 1968, he and Alan Kneese contributed to a US Congress report arguing that economic theory was at odds with the first law of thermodynamics: materials could not be "consumed" physically. Rather, emissions and wastes from economic activity could only be reduced by lowering the physical input into the economy. This material balance approach was truly revolutionary for the environmental and economic thinking of that time; it predated the book by Georgescu–Roegen (1971) which is widely regarded as one of the seminal works in ecological economics. The material balance approach provided the theoretical base for what today has become material flow accounting (MFA) as well as part of a number of nations' public statistics. Ayres's initial MFA application was for emissions from metal processing activities in the New Jersey–New York area (Ayres and Rod 1986), followed by a comprehensive study of chlorine (Ayres 1997, 1998, Ayres and Ayres 1997, 1999). In the same general time period, the MFA approach was also developed in Switzerland by Baccini and Brunner (1991), who produced an important book on the topic.

The distinction between bulk MFA and SFA was described by Bringezu and Moriguchi (2002), who categorized analyses from the perspective of substances, materials, products, firms, and geographical regions, although MFA studies tended to dominate early efforts.

The first metal-specific SFA was directed at zinc in the United States over the period of 1850–1990 (Jolly 1993); it showed that about three-quarters of potential zinc losses to the environment were due to dissipative uses and landfill disposal. Other early MFA studies included those for cobalt in the United States (Shedd 1993), vanadium in the United States (Hilliard 1994), and cadmium in the Netherlands (van der Voet et al. 1994). In another early effort, Socolow and Thomas (1997) produced a MFA study for lead in the United States that called for the integration of risk analysis and highlighted the importance of recycling and technological transformation. A seminal dynamic study (i.e., a time-dependent SFA) was completed for aluminum in Germany by Melo (1999).

By 2000–2010, MFAs had been completed for most metals and in several countries (Chen and Graedel 2012) and for some polymers (Kleijn et al. 2000; Diamond et al. 2010; Kuczenski and Guyer 2010). Data challenges continue to constrain the accuracy of these studies, and resource flows and stocks are highly dynamic, but the methodology is firm, and the results thereby produced have proven directly relevant to corporate and public policy (e.g., Pauliuk et al. 2012).

3.4 Socioeconomic Metabolism

Industrial ecology is often viewed as a natural science in that it tends to be directed at the quantification of such things as use of resources, emissions, recycling rates, and the like. These concerns are, of course, a consequence of human action. This realization inspired in the early to mid-1990s the specialty of socioeconomic metabolism, in which material input, processing, energy use, and loss are quantified and viewed from a socio-technical perspective (see Chap. 6). The ultimate task of this area of study is to relate resource transitions to societal change and to prospects for and measurement of sustainability (Fischer-Kowakski and Haberl 1998; Moriguchi 2001). A principal manifestation of this approach is the studies of economy-wide material flows at the level of various societal units, often on a national level.

Use of MFA of national economies began to surge in the 1990s, beginning with those independently developed for Austria (Steurer 1992), Germany (Schütz and Bringezu 1993), and Japan (Japanese Environment Agency 1992). The material flow balance approach was extended to consider transnational resource extractions induced by domestic demand and to indicate the total material use of an economy, including the so-called ecological rucksacks (Bringezu 1993; Bringezu and Schütz 1995). Bringezu (1993) related the ecological rucksack idea to national material flow balances, accounting for the ecological rucksacks of domestic production of raw materials (e.g., unused extraction) and the ecological rucksacks of imports and exports. This method provided the basis for the first international comparisons through the *Resource Flows* report (Adriaanse et al. 1997).

National material accounts (NMAs) began with a collaborative study among researchers from Germany, Japan, the Netherlands, and the United States (Adriaanse et al. 1997). An important contribution of this study was the identification and quantification of ecological rucksacks, or "hidden flows" – flows such as mineral wastes and agricultural debris. A subsequent effort (Matthews et al. 2000) added Austria to the group of countries that were represented and emphasized waste and hazardous material outputs.

National MFAs aggregate a variety of material inputs and outputs, generating thereby a number of indicators for the material use of national economies that have become internationally standardized, among them "domestic material input (DMI)," "domestic material consumption (DMC)," and "total material requirement (TMR)" (Fischer-Kowalski et al. 2011).

NMAs have now been completed for many countries and have become a required output of statistical offices in European countries. Bringezu et al. (2003, 2004) and Weisz et al. (2006) have compared the results of NMAs for a number of countries and found (among many other features) that the domestic material input per capita had not been decoupled on an absolute basis from gross domestic product per capita. At present, there exist NMAs for almost all countries of the world, documenting annual material extraction and use as well as trade for the past several decades (Schaffartzik et al. 2014).

3.5 Input–Output Analysis

Input–output tables (IOT) in economics quantify the transactions that occur between different industrial sectors in an economy. They are expressed as flows from one sector to another measured in either monetary or mixed units. After some early thoughts on how economics and industrial practice might be linked (Leontief 1970; Ayres 1978; Forsund 1985), IOA was proposed as relevant to industrial ecology in 1992 (Duchin 1992). The extension of IO tables to include specific data about industrial/environmental problems followed fairly soon thereafter in the form of "environmental IOTs" (EIOTs) or "physical IOTs" (PIOTs) (Lave et al. 1995; Kondo et al. 1998; Lenzen 2001; Nakamura and Kondo 2002).

An increasing number of national statistical offices produce input–output tables on a regular basis, an activity that provides substantial information that industrial ecology can draw upon. Enhancements to the earlier EIOT and PIOT methodologies have now rendered input–output analysis increasingly relevant to industrial ecology and increasingly practiced with the field (Suh 2009). Several environmentally extended input–output databases covering the global economy are now available (see Chap. 8). Empirical studies using IO databases are used to analyze problems of concern in industrial ecology; examples are Nakamura and Kondo (2009) on waste management (see Chap. 12) and Lopez–Morales and Duchin (2011) on water management. In addition, a number of environmentally extended multiregional input–output models allow the attribution of globally extracted natural resources to individual countries and economic sectors worldwide (Wiedmann et al. 2013).

3.6 UrbanMetabolism

In principle, urban metabolism might not necessarily be regarded as a distinct branch of the field, because it merely applies industrial ecology tools in a specific spatial location. In practice, however, cities are centers of population, of resource use, and of waste generation, and the data available for such systems is often richer than elsewhere. As a consequence, urban metabolism has become a subspecialty of industrial ecology and one that is increasingly widely practiced (see Chap. 4).

The concept of urban metabolism is attributed to a 1965 paper by Wolman. One of the earliest studies of a quantified urban metabolism is Newcombe et al.'s analysis of resource flows in Hong Kong (1978). This exceptionally detailed study, still a model for today's efforts, quantified flows of human and animal food, glass, plastics, sewage, sulfur dioxide emissions, and much more. This effort was repeated a quarter-century later (Warren-Rhodes and Koenig 2001), demonstrating strong per capita increases in food, water, and material consumption. Researchers in Europe took up the challenge, with examples in Switzerland (Brunner et al. 1994; Baccini 1996) and Sweden (Bergbäck et al. 2001) at about the same time period. Newman (1999) discussed the concept in some detail and applied it to Sydney. Urban industrial ecology is now rather common, a recent example being a metabolic analysis of six Chinese cities (Zhang et al. 2009).

3.7 Industrial Symbiosis

Industrial symbiosis is the organization of industrial organisms and their processes so that "the effluents of one process… serve as the raw material for another process" (Frosch and Gallopoulos 1989). Such arrangements occur because they make good business sense, often because of the proximity of facilities discarding resources to those reusing them, as in Kalundborg, Denmark (Anonymous 1990; Ehrenfeld and Gertler 1997). Increasingly, these systems are recognized as having significant environmental benefits as well (Klee 1999).

Many additional examples of industrial symbiosis have been described (e.g., Schwarz and Steininger 1997; Van Beers et al. 2007), and in the first few years of the twenty-first century, industrial symbiosis methodology became better codified (Chertow 2000). Industrial symbiosis is today recognized as a path to improved operational performance as well as to improved environmental performance in situations where resource exchanges can be efficiently achieved (see Chap. 5).

4 Becoming a Scholarly Field

4.1 Conferences

The first regular conferences in the field of industrial ecology were the IEEE Symposium on Electronics and the Environment that began in 1993 (they have been held each year since, now under the name International Symposium on Sustainable Systems and Technology). At about the same time, the AT&T Foundation began to award university grants for research in industrial ecology (Alexander 1994) and hosted invited meetings of largely industrial and academic participants each year from 1994 to 1997 (Laudise and Taylor-Smith 1999).

Having attended Gordon Research Conferences (GRC) on corrosion science in the late 1980s, one of the authors (T.E.G.) conceived the idea of organizing a GRC on industrial ecology. The 1996 proposal was successful, and the first GRC/IE was held in New London, New Hampshire in 1998. For the first few (biennial) conferences, it was a challenge to attract more than about 80–90 participants, and the conference was on probation during those years. Since that time, the value of a relatively small week-long meeting with invited speakers has become widely appreciated. The GRC/IE now routinely "sells out" at about 140–150 attendees, however, and has been held in the United Kingdom, Switzerland, and Italy as well as in the United States.

The IEEE and AT&T meetings gradually became less central to the field as the Gordon Research Conference on Industrial Ecology began and as the International Society for Industrial Ecology (ISIE) began its own biennial conferences; the first was held in the Netherlands in 2001. Regional ISIE conferences are now held as well, and the industrial ecology field has reached the point where colleagues from around the world meet each other at regular intervals on one continent or another around the world.

4.2 Scholarly Journals

A key attribute of a scholarly specialty is the professional journals in which the research of the field is published. In industrial ecology, the most widely known of these is the *Journal of Industrial Ecology* (*JIE*), whose first issue was published in 1997, predating the formation of ISIE by several years.

The genesis of the *JIE* was a meeting of international leaders in the emerging field in 1995. Convened by the Yale School of Forestry & Environmental Studies in collaboration with programs at MIT and UCLA and with funding from the AT&T Foundation, the meeting participants expressed substantial support for a peer-reviewed journal. MIT Press was chosen as the publisher and Yale University agreed to own the journal. The *JIE* aimed to reach both academics and professionals and helped link the North American industrial ecology community to researchers in Europe and Japan that were active in cleaner production and life-cycle assessment and to other researchers working in material flow analysis.

The *JIE* evolved as the market for academic journals changed. What began as a print-only quarterly journal progressed by adding electronic publication; supporting information on the Web, online early release of articles, article-level open access, and expansion of content, the last by transitioning to bimonthly publication (2008) and by increasing the size of the printed page (2012). In 2015 the journal shifted on online-only. Translations of abstracts of all journal articles into Chinese began in 2001 with support of the Henry Luce Foundation. The *JIE* changed publishers to Wiley–Blackwell in 2008.

Edited by Reid Lifset since its inception, it has published path-breaking issues on bio-based products largely before biofuels, and bio-based products became the intense focus of LCA and GHG emissions research, on e-commerce, bringing rigor to the discussion of whether bits replacing atoms has a desirable environment impact, and nanotechnology, drawing attention to the environmental impacts of nano-manufacturing which had been ignored in many parts of the world.

Other journals with substantial industrial ecology content are *Resources, Conservation, and Recycling* (first issue 1988), and the *Journal of Cleaner Production* (first issue 1993). Industrial ecology research and assessments have appeared as well in many additional journals, including *Ecological Economics* (e.g., Bringezu et al. 2004), *Environmental Science & Technology* (e.g., Graedel 2000), *Proceedings of the National Academy of Sciences of the U.S.* (e.g., Rauch 2009), *Nature* (e.g., Lenzen et al. 2012), and *Science* (Reck and Graedel 2012). It is clear that there is no longer a shortage of places for industrial ecology papers to be published or a lack of editors willing to accept them if they are of satisfactory quality.

4.3 The International Society for Industrial Ecology

By the late 1990s, it was apparent that the field of industrial ecology needed to organize itself into a professional society. The issue was discussed in detail in a meeting hosted by Jesse Ausubel at the New York Academy of Sciences in 2000. Once again, support was provided by the AT&T Foundation. Based on the consensus of the international group, the International Society for Industrial Ecology was launched a year later with the *Journal of Industrial Ecology* as its official journal. The Yale School of Forestry & Environmental Studies agreed to serve as the temporary international secretariat for the ISIE. As the society and the industrial ecology community grew, the ISIE created sections focused on industrial symbiosis/eco-industrial development, socioeconomic metabolism, life-cycle sustainability assessment, organizing sustainable consumption and production, sustainable urban systems, and environmentally extended input–output analysis. More intangibly, but perhaps more importantly, the ISIE provides continuity, an opportunity for interaction and, along with the *JIE*, academic legitimation for those seeking to work in industrial ecology.

4.4 Courses and Textbooks

As with any scholarly field, training the next generation is important, and doing so requires pedagogical materials. Aside from scholarly journal articles, several textbooks have been produced for use in industrial ecology-related programs in various academic fields. They include *Industrial Ecology* (Graedel and Allenby 1995 [Japanese translation, 1996]); 2nd edition, 2003 [Korean translation, 2004; Chinese translation, 2005; Russian translation, 2006]), *Green Engineering: Environmentally Conscious Design of Chemical Processes* (Allen and Shonnard 2002), *Applied Industrial Ecology: A New Platform for Planning Sustainable Societies* (Erkman and Ramaswamy 2003), *Industrial Ecology: konzeptionelle Grundlagen, zentrale Handlungsfelder, Kernwerkzeuge und erfolgreiche Praxisbeispiele* (Isenmann and von Hauff 2007), *Industrial Ecology Management: Nachhaltige Entwicklung durch*

Unternehmensverbünde (Von Hauff et al. 2012); *Crossing "Environmental Mountain" – Study on Industrial Ecology* (Lu 2008), *Ecologia Industrial* (Ferrao 2009), *Environmental Engineering: Fundamentals,Sustainability, Design* (Mihelcic & Zimmerman, 2009, 2nd edition, 2014), and *Industrial Ecology and Sustainable Engineering* (Graedel and Allenby 2010).

The first formal course in industrial ecology was apparently taught at the Norwegian University of Science and Technology in 1993 (Marstrander et al. 1999). A few years later, the Delft University of Technology and Philips Consumer Electronics jointly developed modules for teaching eco-design in industry and in universities (Stevels 2001). From that beginning, a number of universities in Europe and North America began offering industrial ecology courses in the latter 1990s and the early 2000s (Cockerill 2013). This area of study is growing rapidly: a recent survey identified industrial ecology courses and/or programs at 190 universities and colleges in 46 countries (Finlayson et al. 2014). As with many young fields, the scope, level, and content of these courses have considerable diversity, but it is clear that education in industrial ecology is widespread, growing, and evolving.

5 Epilogue

This review and recollection emphasizes the first decade or so of the industrial ecology field, largely because the authors had the good fortune to be involved in most of the developmental activities that occurred during that period and because many aspects of those activities are not very widely known. It is a great pleasure to us that the industrial ecology field has grown enormously in size and influence since its founding and has become "the science behind sustainability." It will be interesting and rewarding to watch industrial ecology's further development in the years to come.

Authors' Note Because we are not historians, this contribution inevitably emphasizes our own interactions and experiences at the close of the twentieth century. It also has a North American bias, partly because some of the most significant parts of industrial ecology's early days occurred there and partly because that is where we live. We are, however, grateful for the comments and suggestions from Faye Duchin, Marina Fischer-Kowalski, and Stefan Bringezu which have significantly improved an earlier version of this work. For what we perceive will be of maximum utility to most readers, the references are largely restricted to English.

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